APPLICATION OF ULTRAVIOLET DISINFECTION IN A TERTIARY WASTEWATER TREATMENT PLANT

RESEARCH REPORT No. 87

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Ministry
of the
Environment

Ontario

The Honourable
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Minister

Gérard J. M. Raymond
Deputy Minister

APPLICATION OF ULTRAVIOLET DISINFECTION

IN A TERTIARY WASTEWATER TREATMENT PLANT

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BY

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Note: Use of Trade Names in this Report is not to be construed as Ministry of the Environment endorsement of the equipment.

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ABSTRACT

The applicability of UV disinfection technology to a well nitrified and sand-filtered municipal sewage effluent was investigated at the Newmarket WPCP. For this type of effluent UV irradiation is an effective and cost competitive disinfection alternative to chlorination plus dechlorination process.

The UV disinfection unit consistently reduced effluent total and fecal coliforms to 2,500/100 ml and 200/100 ml, respectively when operated under the manufacturer's recommended conditions. Effluent COD concentration was found to be a useful surrogate parameter to predict UV disinfection efficiency as affected by effluent quality changes.

The cost (amortized capital plus operating) for applying UV disinfection in a well nitrified sand-filtered effluent was estimated to be between 4.33-4.67¢/m^3. This cost is about 1.2-1.3 times the cost for chlorination plus dechlorination process. However, this cost is only 49% and 55% of ozone and chlorine dioxide disinfection costs, respectively.

During the study the quartz sheaths were hand-brushed every twenty-four hours of continuous operation to free them from fouling by deposits. This observation indicates that an automatic wiping system for the sheaths is essential for all future UV disinfection units.

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CONCLUSIONS

1. In a high quality, biologically treated and filtered sewage effluent, UV irradiation was found to be a promising disinfecting alternative to chlorine.
2. In this study, the log (TC_r/TC_u) was found to be significantly affected by UV dosage measured in terms of number of UV lamps switched-on and effluent COD concentration but was not affected by effluent flow-rate.
3. Using the manufacturer's recommended operating conditions, with sixteen 10.4 watt UV lamps switched-on, and a "gross" nominal exposure time between 8.3 to 9.8 seconds, a median log (TC_r/TC_u) of -3.59 (equivalent to 99.97% inactivation) was attained in an effluent with the following mean quality: turbidity = 3.6 JTU, COD = 21.6 mg/L and TKN = 2.6 mg/L. The corresponding median TC_r was 28/100 ml, and FC_r was 4/100 mL.
4. Using identical operating conditions, a median log (TC_r/TC_u) of -2.07 (equivalent to 99.15% inactivation) was attained in an effluent with mean quality:
   turbidity = 48.8 JTU, COD = 36.3 mg/L and TKN = 6.5 mg/L. The corresponding median TC_r was 1020/100 mL and FC_r was 188/100 mL.
5. Operating experience accumulated during the study indicated that an automatic wiping system for cleaning the quartz sheaths which shield the UV lamps, is essential for continuously operating UV disinfection units.
6. UV disinfection cost in a small WPCP is estimated to be between 4.33-4.67 ¢/m^3, and is therefore, competitive with chlorination plus dechlorination costs.

RECOMMENDATIONS

1. UV irradiation should be considered when dechlorination is required in a well nitrified and sand-filtered municipal sewage effluent.
2. An automatic wiping system to keep the quartz sheaths from fouling by activated sludge solids is needed in all full-scale UV disinfection units.
3. The applicability of UV irradiation technology should be further evaluated in the more typical municipal sewage effluents such as nitrified and non-nitrified secondary effluents.
4. The effectiveness of UV irradiation on some selected pathogens commonly found in sewage effluents should be included in future studies.
5. The utility of "percent UV transmission" measured in a 1-cm cell, at 254 mm wavelength as a process monitoring parameter should be assessed.

1.0 INTRODUCTION

Chlorine is the most widely used water and wastewater disinfectant in North America. However, serious concerns have been expressed by many environmentalists on its continued use. Chlorine residuals have been shown to be persistent (1,2) and toxic to aquatic life at extremely low concentrations (3,4). Hazardous chlorinated organics have also been identified in chlorine disinfected potable water (5), and sewage effluents (6). Such concerns have prompted the search for an economically and technically feasible alternative disinfectant to replace chlorine. Chlorine dioxide, bromine chloride, ozone and gamma ray irradiation have been extensively investigated in the past (7,8,9,10). Unfortunately, these alternative disinfectants were either too expensive or produced acute toxicity to aquatic organisms in the disinfected effluents.

Ultra-violet light, generally known as UV light is commonly applied in hospital and food industries for sterilizing air and process water. However, its application for potable water and wastewater disinfection has not received much attention in the past (see Section 3.1). As part of an on-going disinfection research program of the Ministry of Environment, this field investigation was conducted to determine the applicability of UV disinfection in a typical Ontario tertiary WPCP.

2.0 OBJECTIVES AND SCOPE

2.1 Objectives

The principal study objective was to determine the feasibility of disinfecting a highly nitrified, biologically treated, and sand-filtered sewage effluent with ultra-violet light.

The secondary objective was to conduct a preliminary assessment of the quantitative effect of UV dosage, and effluent quality on the bactericidal efficiency of UV light.

2.2 Scope

The feasibility of disinfecting a highly nitrified effluent was investigated in a municipal tertiary WPCP, with a pilot scale proprietary UV unit. The practicality of UV disinfection was evaluated in terms of two criteria. In order to allow a cost-effectiveness comparison with chlorine disinfection developed in an earlier study (7), the first criteria was defined as:

- ability displayed by the proprietary UV disinfection unit to consistently achieve the following bacteriological quality in the disinfected effluent:

1) a geometric mean or median total coliform survival density equal to or less than 2,500/100 ml. The mean or median value must be derived from a minimum of 10 samples;
2) and total coliform survival density must be equal to or less than 5,000/100 ml at one standard deviation or at 85 percentile.

The second criteria was based on the amount of time and effort required to maintain the UV disinfection unit in proper working conditions.

3.0 LITERATURE REVIEW AND DEVELOPMENT OF A SEMI-MECHANISTIC MODEL FOR UV DISINFECTION DATA ANALYSIS

3.1 Literature Review

The bactericidal property of UV irradiation was first discovered by Downes and Blunt in 1878 (11). From then on much effort was spent on developing its application to dry air, potable water and to a much smaller extent to sewage effluent disinfection. The bactericidal mechanism of UV irradiation, and factors causing interference to its effectiveness were also extensively researched. Detail literature reviews on these subjects have been made by many authors such as Oda (12), Cheng (13), and more recently by Duff (14). This section is therefore, restricted to reviewing the findings of fairly recent studies, and references needed to establish a useful semi-empirical mechanistic model for analysing UV disinfection data.

Yip and Konasewhich (15) found that UV light could be absorbed by many contaminants commonly found in sewage effluents, such as ferrous ion, humic substances, lignin sulfonate, and phenolic compounds, etc. The presence of activated sludge solids can also significantly reduce the effectiveness of UV disinfection in sewage effluents. Bacterial organisms often tend to accumulate within the solids and are therefore, well protected from UV irradiation (14,15). As a consequence, the application of UV disinfection to sewage effluent was not seriously considered in the past.

In 1976, Oliver and Carey (16) proved UV irradiation to be an environmentally safe, and efficient disinfectant. No toxicity to juvenile rainbow trout was observed in the short-term bio-assay tests conducted with UV disinfected secondary effluent. In 1978, Jolly et al (17), using GC analysis found that UV irradiation produced the least chemical changes in a secondary effluent when compared to chlorination and ozone disinfection. Promising bactericidal results were reported by Wolf (18), Johnson (19), Scheible (20), and Severin (21). In all four studies, secondary effluents disinfected with UV irradiation resulted in better than 99.7% inactivation of fecal coliforms and/or total coliforms. Wolf (18) and Severin (21) also observed that UV disinfection efficiency was not significantly affected by suspended solids in the range of 5 mg/L to 50 mg/L, and by turbidity in the range of 0.5 to 12 NTU. Huff (22) noted in his study that UV disinfection efficiency was not significantly affected by iron concentration up to 3.7 mg/L.

3.2 Development Of A Semi-Mechanistic Model

At present, a quantitative relationship between bacteriological inactivation efficiency and UV intensity, exposure time, and effluent quality has not been well defined. Most field studies up to now were simply devoted to investigating the feasibility of applying UV disinfection technology in high quality sewage effluents. Excessive UV dosages were often applied and operating conditions such as UV intensity and nominal exposure time were seldom changed. Consequently, the optimum UV dosage, and process control strategy for typical Ontario effluents cannot be readily estimated.

It is therefore, attempted in this study to develop a semi-mechanistic model which will allow a better understanding of the quantitative relationship between bactericidal efficiency of UV irradiation, process operating parameters and effluent quality.

Jagger (23) postulated that inactivation of "one" bacterial organism by UV irradiation is caused by the adsorption of "one" photon. In a typical UV disinfection unit where there is a continuous supply of photons, the rate of decrease in the number of active bacterial organisms "M" with respect to UV dose "D" is therefore, proportional to the number of active organisms surviving at that dose level. Mathematically, this relationship is described by the Chick's Law of first order of inactivation kinetics:

$$-(dM/dD) = K_o M \tag{1}$$

where K_o = rate constant to be evaluated experimentally. Integrating equation (1), and then taking logarithmic transformation on both sides of the integrated equation, Chick's Law for UV disinfection becomes:

$$\mathrm{Log}_{10}(M_r/M_u) = -K_o D \tag{2}$$

where M_u, M_r = number of bacterial organisms before and after UV irradiation, respectively.

UV dose "D" is defined by the Reciprocity Law (24) as:

$$D = It_a \tag{3}$$

where I = UV intensity received by the inactivated bacterial organisms (micro-watts/cm^2);

t_a = "true" exposure time; i.e. the time which the inactivated bacterial organisms are actually exposed to UV irradiation (seconds).

In sewage disinfection, part of the UV intensity emitted by the UV lamps is absorbed by various contaminants before reaching the bacterial organisms. The magnitude of UV intensity measurable at a distance "L_o" from the source can be estimated by a modified form of Beer's Law (29):

$$I_p = I\ 10^{-\Sigma E_i C_i L_o} \qquad (4)$$

where I_p = magnitude of UV intensity measured at distance "L_o" from the source;

I = UV intensity emitted by an UV lamp;

E_i = extinction coefficient which is specific to the wavelength of the radiation emitted and the nature of the i th interfering contaminant;

C_i = concentration of the i th interfering contaminant;

Σ = summation sign indicating the synergistic effect of n number of contaminants.

The intensity emitted by an UV lamp is known to decrease very gradually with time. However, over a short period of continuous operation, each UV lamp within a disinfection unit can be assumed to emit equal and constant UV intensity "I_o". For simplicity, it is further assumed in this study that for small changes in effluent quality (i.e. small changes in C_i) the average magnitude of UV intensity "I_{ave}" available for disinfection within a given unit is numerically equal to the intensity measurable at a fixed point of

constant distance "L" from the source i.e.

$$I_{ave} = I_o 10^{-(\Sigma E_i C_i)L} \tag{5}$$

Equation (3) suggests that UV dosage "D" can be regulated by means of adjusting either effluent exposure time "t_a" or UV intensity emitted by the lamp "I_o". However, specially constructed UV lamps, dimming ballasts, and intensity selecter are needed for the latter approach. Consequently, UV dosage in most proprietary units can only be varied by means of regulating effluent exposure time.

The true exposure time "t_a" is usually difficult to determine in continuous flow systems, since back-mixing, short-circuiting and other non-ideal flow conditions always exist in fullscale and pilot scale reactors. Instead, nominal exposure time "t" defined as:

$$t = \frac{\text{Volume of Reactor}}{\text{Volumetric Effluent Flowrate}} \tag{6}$$

is often used. It is generally believed that UV light is able to penetrate only a very short distance through contaminated liquid medium, such as sewage effluent (27). The rate of total coliform and other bacterial organisms inactivation is therefore, significant only at close proximity of the irradiating UV lamps; in another words, the effective reactor volume can be much smaller than the physical volume of the reactor. For the purpose of simplicity, the effective volume "V_e" around each lamp is assumed to be constant for small changes in effluent quality. In the absence of interaction among the switched-on UV lamps total effective volume "V_{te}" within a disinfection unit is linearly proportional to the number of UV lamps switched-on

"N".

$$V_{te} = NV_e \tag{7}$$

where N = number of UV lamps switched-on

Hence, nominal exposure time can be re-defined as:

$$t = (NV_e)/F \tag{8}$$

where F = effluent flowrate through the unit.

Substituting equations (5) and (8) into equation (3), UV dosage "D" can be re-defined as:

$$D = (I_o V_e)\ (N)\ (1/F)\ 10^{-(\Sigma E_i C_i)L} \tag{9}$$

Theoretically, UV dosage can be doubled by either doubling N, or reducing F by half. However, in practice switching UV lamps on/off can result in a complex change in the interaction patterns between lamps and reactor walls and baffles (26). Furthermore, hydraulic characteristics such as the degree of short-circuiting, and/or back-mixing, vary with effluent flowrate. To account for the above non-ideal conditions, a more general equation for defining UV dosage "D" is used in this study:

$$D = (I_o V_e)\ N^{K_1}\ F^{-K_2}\ 10^{-(\Sigma E_i C_i)L} \tag{10}$$

where K_1, $-K_2$ = arbitrary exponents for correcting the different effects of N and F exerted on D, respectively.

Substituting equation (10) into equation (2), and also replacing M_u and M_r by total coliform counts/100 mL "TC_u, TC_r",

equation (11) is derived:

$$Log_{10}\ (TC_r/TC_u) = -K_o\ (I_oV_e)\ N^{K_1}\ F^{-K_2}\ 10^{-(\Sigma E_iC_i)L} \tag{11}$$

Since I_o, V_e, and L are assumed to be constants, equation (11) can be simply expressed as:

$$Log_{10}\ (TC_r/TC_u) = -K_o'\ N^{K_1}\ F^{-K_2}\ 10^{-\Sigma(J_iC_i)} \tag{12}$$

$$\text{where } K_o' = K_oI_oV_e \tag{13}$$

$$J_i = E_iL \tag{14}$$

The constant terms K_o', K_1, $-K_2$, and J_i can be experimentally determined by linearizing equation (12) to the form of:

$$\begin{aligned} Log(Log_{10}(TC_r/TC_u)) = {} & Log_{10}K_o' + K_1\ Log_{10}(N) \\ & + (-K_2)\ Log_{10}\ (F) \\ & + \Sigma(-J_iC_i) \end{aligned} \tag{15}$$

4.0 DESCRIPTION OF THE NEWMARKET WPCP AND ITS OPERATION

The Newmarket WPCP is a tertiary sewage treatment plant with a design capacity of $1.4X10^4$ m^3/day. Raw sewage received by the WPCP is principally from residential sources. Treatment facilities in the WPCP include: grit removal, primary clarification, conventional activated sludge treatment, chemical coagulation with ferric chloride, final clarification, sand-filtration and chlorine disinfection.

During the study, daily average sewage flowrates fluctuated between $1X10^4$ to $1.2X10^4 m^3$/day. Peak flowrates up to 2½ times the average flowrate generally occurred between 1000 hour and 1500 hour. Ferric chloride was added for phosphorus removal at about 10 mg/L as total iron. The effluent was always highly nitrified, and was disinfected with 27.2 Kg/day gaseous chlorine to maintain a total available chlorine residual of 0.1 mg/L (measured by OTA colorimetric method), at the end of a 30 minute contact time.

Figure 1 : An Overview of the uv Disinfection Unit
(Aquafine Model WT-60) Used for the Study

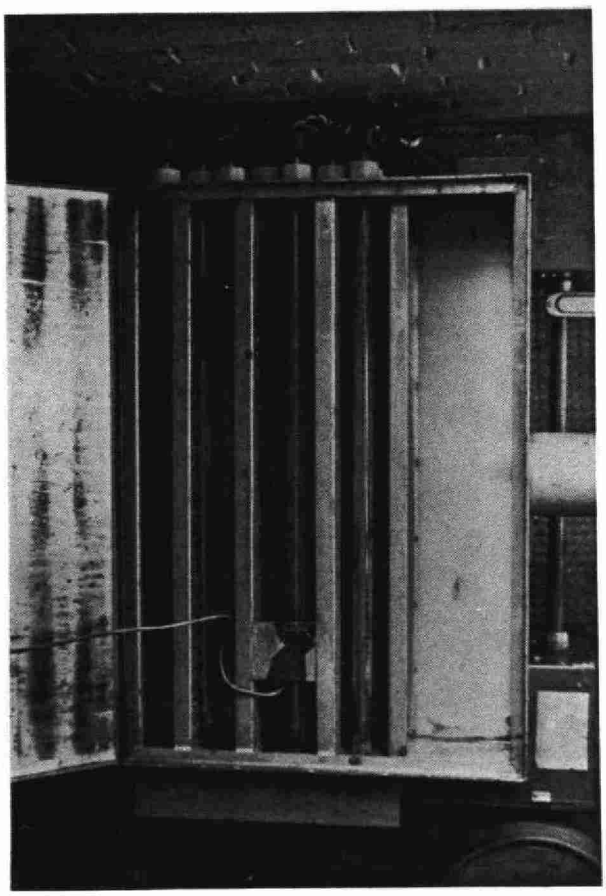

Figure 2 : An Overview of the Internal Structure of
The uv Disinfection Unit

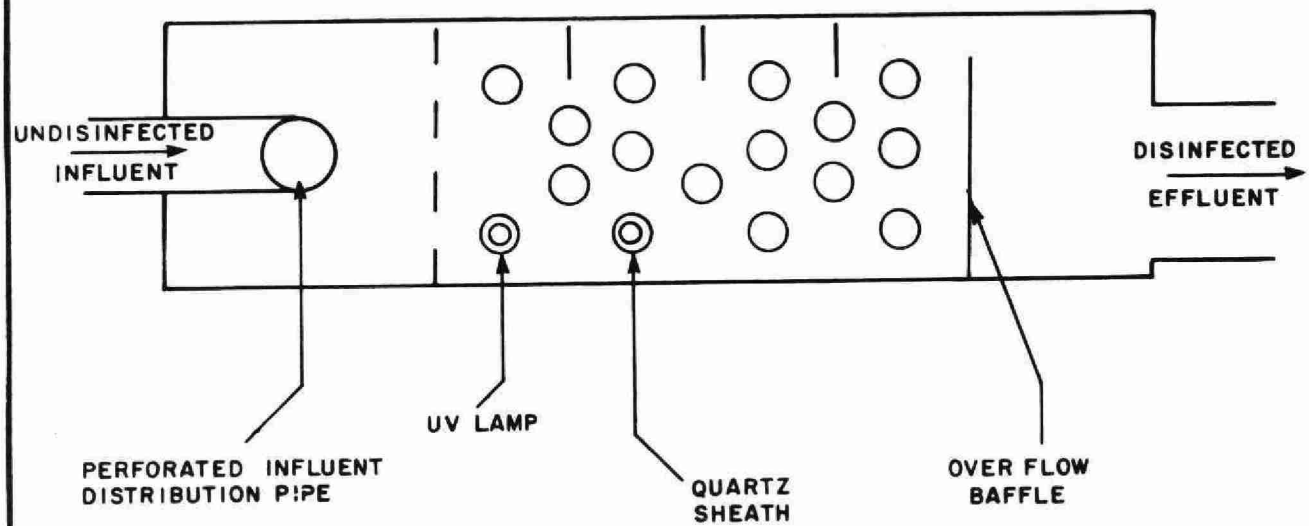

Figure 3 : Schematic Diagram of the uv Disinfection Unit Studied

5.0 MATERIALS AND METHODS

5.1 UV Disinfection Unit (Aquafine Company, Model WT-60)

Figures 1 and 2 are pictures (front and top views) of the UV disinfection unit used for this study. Figure 3 is a schematic diagram (front view) of the unit. The unit is a total submerged-lamp system, manufactured by the Aquafine Corporation of California, USA. The disinfection chamber (0.36 m by 0.75 m by 0.15 m, LXWXD) is totally enclosed within a small (0.71 m by 0.75 m by 0.18 m) stainless steel tank. The net chamber volume (i.e. gross chamber volume less lamp volume) is 34.6 L.

Effluent is disinfected in the chamber by sixteen low-pressure mercury ultra-violet lamps manufactured by General Electric (Model G36T6). Each lamp is 19 mm in diameter and 0.75 m long, and enclosed within a quartz sheath of 25 mm diameter. The radiance at $72^{o}C$, and at 51 mm distance in air is quoted by the manufacturer to be $5.22X10^{4}$ micro-watts/cm^{2}. The manufacturer estimated that approximately 6% to 8% of the intensity will be lost when UV light transmits through the quartz sheath.

The UV lamps are placed at five different depths beneath the liquid surface and are arranged in seven rows, perpendicular to the effluent flow direction. The UV lamps are automatically switched-off when the cover of the tank is opened. A 50 mm diameter by 640 mm long perforated pipe is used to disperse the sewage influent across the width of the tank. Further mixing is promoted by four sets of shallow baffles within the disinfection chamber. The number of UV lamps in service is indicated on two light emitting diode displays. A model S-254 optical sensor is provided

with the unit for measuring UV intensity at a fixed point. This measurement will be referred to as UV "Point" intensity. The sensor is located at 13 mm directly above one of the UV lamps. It is claimed to be capable of responding to 90% of the intensity transmitted by the UV lamps for wavelengths within the germicidal range (250 nm to 270 nm). The sensor is calibrated in an arbitrary scale of zero to 100 units, rather than in absolute units of micro-watts/cm^2. A zero unit intensity reading implies no UV intensity detected at the point of measurement, while 100 unit intensity reading implies maximum intensity detected. The sensor is intended to serve as a gross indicator of the degree of fouling on the quartz sheaths, and gives an early warning to operators when adverse effluent is encountered.

The manufacturer recommends the UV disinfection unit to be operated at or below a maximum effluent flowrate of 227 L/min, and with all sixteen UV lamps switched-on. Since the effective volume around each UV lamp "V_e" cannot be physically measured, instead the net volume of the disinfection chamber (34.6 L) was used to calculate the nominal exposure time which will be referred to as "gross" nominal exposure time "t_s". When the unit was operated at the recommended capacity "t_s" was estimated to 9.2 seconds.

Hydraulic characteristics of the disinfection unit at several flowrates were evaluated by dye-tracer studies. A brief interpretation and discussion of the dye-tracer results are given in Appendix 1.

5.2 Experimental Procedures

5.2.1 UV Disinfection Studies

Except for a few days when the disinfection unit was shut down for various reasons, it was operated continuously from mid-March to mid-October. However, samples for bacteriological and physical-chemical quality analyses were taken only on a few selected days.

Effluent for UV disinfection was delivered to the disinfection unit by a submersible pump. Figure 4 is a schematic flow diagram of the experimental setup. In order to obtain a greater variation in effluent quality, pre-sand filtered, sand filtered and mixtures of the two effluents were disinfected. In most runs, a constant effluent flowrate of 227 L/min was pumped through the disinfection unit. Effluent flowrate was controlled by two 51 mm gate valves. Instantaneous flowrate was measured by a pair of "S&K" rotameters, and total volume of effluent disinfected over a time period "t" was measured by a 51 mm Neptune water meter.

The disinfection unit was not equipped for continuous variation of total UV intensity. In most runs, UV dosage was varied in steps by switching-off pairs of UV lamps in succession. The electrical power (watts) required to energize different numbers of UV lamps was measured during each run by a watt-meter. Effluent flowrate was varied only in a limited number of runs.

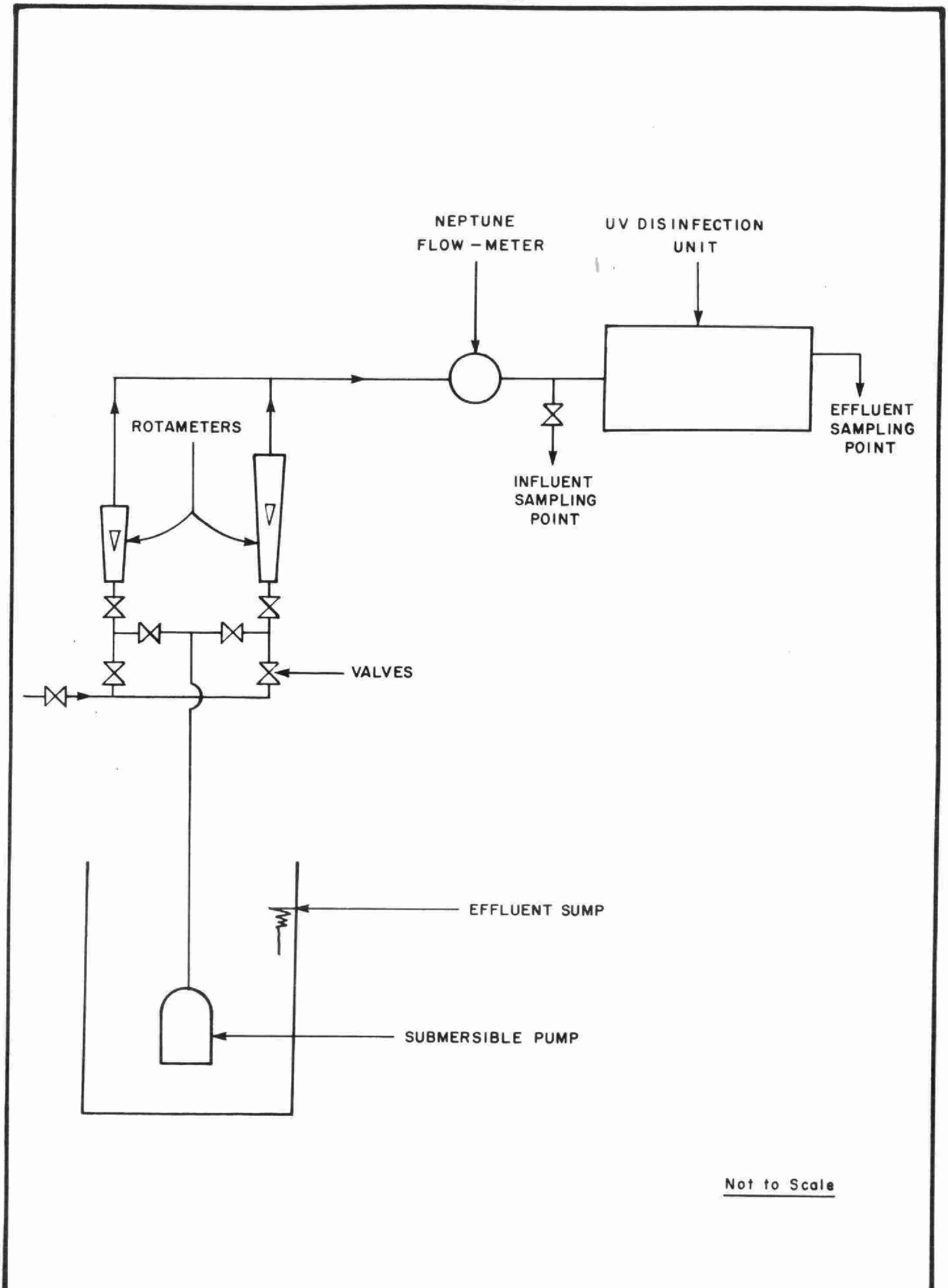

Figure 4 : Schematic Diagram For Effluent Distribution And Flowrate Control System

To obtain maximum UV intensity transmitted through the quartz sheaths, the sheaths and baffles were hand-brushed one-half-hour before sampling (approximately equivalent to 180 "gross" nominal exposure times). Samples for bacteriological and physical-chemical analyses were always taken together. Disinfected and undisinfected effluent samples were collected directly into standard Ministry of the Environment sample bottles. The bacteriological sample bottles did not contain $Na_2S_2O_4$. All bacteriological analyses were completed within 24 hours of sampling by the MOE Microbiological laboratory. During transportation, the bacteriological samples were not wrapped to prevent exposure to sunlight. Chemical analyses were carried out by the MOE, Water Quality Laboratory. Turbidity and colour were measured on-site with a "Hach-Kit" turbidity meter and colour disc comparator. All laboratory analyses were carried out according to the standard Ministry of the Environment methods (30).

5.2.2 Evaluation Of Lamp Sheath Fouling

Past experience has shown that activated sludge solids in biologically treated sewage effluent tend to adhere easily onto the quartz sheaths (27), resulting in a significant decrease in the amount of effective UV intensity available for bactericidal action. During the entire study, the sensor was in proper operating condition only for nine successive working days. Consequently, no UV "Point" intensity readings were taken when bactericidal efficiency was being studied. During the nine days when the sensor

was operational, filtered effluents were continuously pumped through the disinfection unit. UV "Point" intensity was measured with the optical sensor every morning before and after the quartz sheaths were hand-brushed. The difference in "Point" intensity readings (before and after cleaning) was used to assess the degree of fouling of quartz sheaths by solid deposits and the adequacy of hand-brushing the sheaths as a regular maintenance procedure.

6.0 RESULTS AND DISCUSSION

6.1 Experimental Results

The bacteriological and physical-chemical quality data collected during the study are given in Appendix II, Table A.II.1. Twenty-four of the total 47 experimental runs conducted were performed under the manufacturer's recommended operating conditions, i.e. with 16 UV lamps switched-on, and effluent flowrates maintained between 213 L/min and 250 L/min. The remaining 23 runs were conducted with effluent flowrates maintained in the range of 109 L/min to 319 L/min, and/or with fewer number of UV lamps switched-on.

6.2 Bactericidal Effectiveness Of UV Disinfection

Bacteriological results obtained with 16 UV lamps switched-on and effluent flowrates between 213 L/min to 250 L/min, ("gross" nominal exposure times between 8.3 to 9.8 seconds) are presented in Table 1, along with corresponding undisinfected effluent physical-chemical quality parameters. Linear correlation coefficients between $\log_{10}(TC_r/TC_u)$ and each physical chemical quality parameter measured were also calculated and presented in the Table. The Table shows that variation in $\log_{10}(TC_r/TC_u)$ related closely to variations in turbidity and COD concentrations.

In order to facilitate further analysis, data in Table 1 was divided into two groups. Data in the first group had a turbidity below 10 JTU and COD concentration below 30 mg/L. This group will be referred to as "high" quality effluent. Data with turbidity above 30 JTU or COD concentration above 30 mg/L were gathered into the second group, and will be referred to as "low" quality effluent. Average bacteriological and physical-

TABLE 1 - RELATIONSHIP BETWEEN LOG(TC_r/TC_u) AND EFFLUENT QUALITY OPERATING CONDITIONS:

16 UV LAMPS SWITCHED-ON NOMINAL EXPOSURE TIME 8.3-9.8 SECONDS

Log $\frac{TC_r}{TC_u}$	TC_u PER 100 ml	TC_r PER 100 ml	FC_u PER 100 ml	FC_r PER 100 ml	EFFLUENT TEMP. °C	BOD_5 mg/L	COLOUR HAZEN UNIT	SS mg/L	TURBIDITY JTU	TKN mg/L	IRON mg/L	COD mg/L
-5.016	8.3×10^5	8	3.8×10^4	4	10	17	5	10	5.5	5.0	0.74	26
-4.973	9.4×10^5	10	1×10^3	4	21	4	25	6	2.5	1.2	0.40	26
-4.067	1.4×10^5	12	4.2×10^3	4	11	7	5	10	5.5	2.0	0.75	20
-3.954	1.8×10^5	20	3.1×10^4	4	21	7	38	6	5.5	1.2	0.36	23
-3.948	7.1×10^4	8	5×10^3	4	19	4	20	3	1.4	1.1	0.26	21
-3.740	4.4×10^4	8	7×10^2	4	--	9	21	4	1.2	0.8	0.30	17
-3.602	1.6×10^4	4	1.3×10^3	4	--	1	15	3	1.2	0.6	0.19	16
-3.679	2.1×10^5	44	7.7×10^3	4	19	4	21	8	3.5	1.4	0.61	24
-3.587	1.7×10^5	44	1.9×10^4	8	12	---	15	7	5.5	5.8	0.65	23
-3.304	2.9×10^5	144	2.4×10^4	12	12	23	15	26	7.5	6.0	1.7	--
-3.270	6.7×10^4	36	3×10^3	4	19	4	20	3	1.4	1.1	0.26	21
-3.243	2.1×10^4	12	6.3×10^2	4	21	8	26	4	2.0	2.4	0.50	21
-3.220	7.3×10^4	44	6.1×10^3	8	19	7	18	6	4.0	2.4	0.68	21
-3.121	3.7×10^4	28	2.7×10^3	4	18	6	16	7	3.0	1.0	0.54	18
-2.917	3.3×10^4	40	1.0×10^3	4	19	4	2	3	1.4	1.1	0.26	21
-2.881	7.6×10^5	1000	1.0×10^5	4	21	14	32	5	5.5	5.4	0.77	27
-2.760	3.2×10^5	556	3.1×10^4	112	11	10	5	7	4.0	6.0	0.40	20
-2.536	3.5×10^5	1020	2.6×10^4	88	19	4	30	6	33.0	8.4	0.05	34
-2.204	4.8×10^5	3000	8.9×10^4	6000	12	21	15	12	6.5	5.6	1.65	31
-2.155	1.4×10^5	980	2.7×10^5	196	16	9	35	14	89.0	7.4	0.90	40
-2.068	1.4×10^5	940	1.1×10^4	480	16	9	40	16	101	5.6	0.85	42
-1.924	7.9×10^4	940	6.0×10^3	84	16	7	30	10	56.0	4.0	0.22	36
-1.867	1.4×10^5	1900	1.1×10^4	148	18	6	30	7	4.8	8.2	0.12	35
-0.320	1.9×10^4	9.1×10^3	4.7×10^2	188	21	10	10	4	60.0	1.8	0.44	21
Linear Correlation Coefficient Between Log (TC_r/TC_u) and the Parameter.				0.726*	0.264	0.007	0.256	0.096	0.605*	0.375	0.027	0.425*

* Significant at 95% confidence.

chemical quality of the two groups of undisinfected effluents are summarized in Table 2.

Percent frequency distributions of $\log_{10}(TC_r/TC_u)$ for the two effluents are plotted in Figure 5. Similar plots for $\log_{10}(TC_r)$ and $\log_{10}(FC_r)$ are presented in Figures 6 and 7, respectively. Figures 5,6 and 7 clearly illustrate that inactivation of total coliforms were significantly affected by effluent turbidity and COD concentration. The three figures further indicate that only $\log_{10}(TC_r/TC_u)$ and $\log_{10}(TC_r)$ attained in the high quality effluent were normally distributed, while the remaining plots of $\log_{10}(TC_r/TC_u)$ and $\log_{10}(TC_r)$ and $\log(FC_r)$ deviated significantly from normal distribution. These deviations were probably due to insufficient data collected.

To account for the abnormal distribution and for the purpose of consistence, the non-parametric term "median" values rather than the more commonly used term "geometric mean" value were derived from the three figures and are summarized in Table 3. Table 2 and 3 show that in this study, with 16 UV lamps switched-on, and a "gross" nominal exposure time of 8.3-9.8 seconds, when effluent quality deteriorated from "high" to "low" quality, the median total coliform and fecal coliform reductions decreased by approximately one to one and a half order of magnitude. Nonetheless, the desired bacteriological effluent quality (see Section 2.0) was achieved in effluents with turbidity as high as 101 JTU and COD concentration up to 42 mg/L.

TABLE 2 - MEAN BACTERIOLOGICAL AND PHYSICAL-CHEMICAL QUALITY FOR "HIGH QUALITY" AND "LOW QUALITY" UNDISINFECTED EFFLUENTS

EFFLUENT		TC_u*	FC_u*	TURBIDITY JTU	COD mg/L	TKN mg/L	COLOUR HAZEN UNIT	BOD_5 mg/L	SS mg/L	TOTAL IRON mg/L
	A. MEAN	1.2×10^5	5.7×10^3	3.6	21.6	2.6	18	8.0	6.9	0.6
"HIGH"	STD. DEV.	3.56	4.83	2.0	3.2	2.1	10	5.7	5.4	0.4
QUALITY	NO. OF DATA	17	17	17	16	17	17	16	17	17
"LOW"	A. MEAN	1.3×10^5	2.8×10^4	50.0	34.1	5.9	27	9.4	9.9	0.60
QUALITY	STD. DEV.	2.87	4.29	37.6	6.9	2.4	1	5.5	4.4	0.57
	NO. OF DATA	7	7	7	7	7	7	7	7	7

NOTES: IN LIEU OF ARITHMATIC MEAN AND STANDARD DEVIATION; *GEOMETRIC MEAN AND COEFFICIENTS OF VARIATION ARE REPORTED FOR TC_u AND FC_u.

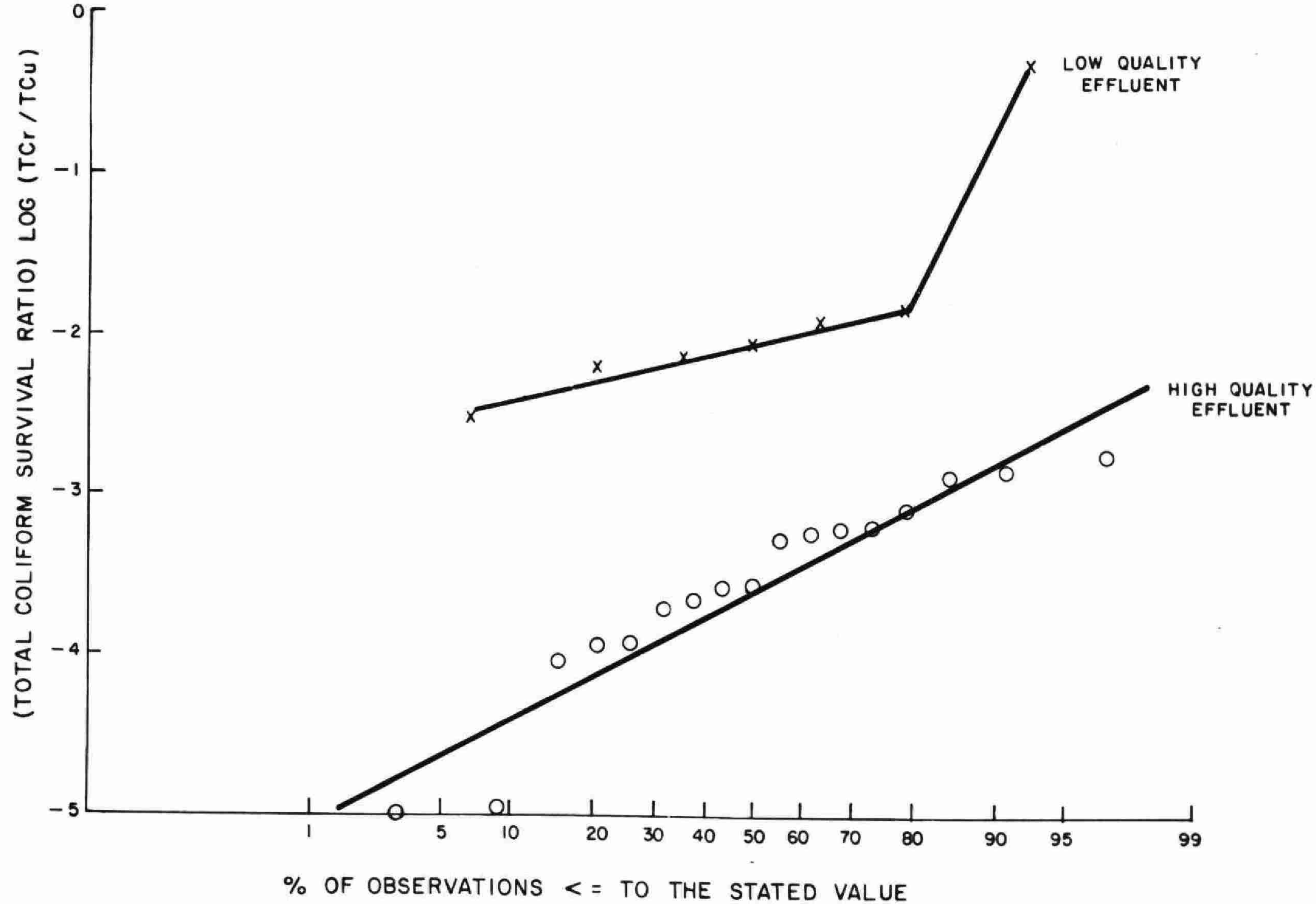

Figure 5 : Percent Frequency Distributions of Log (Total Coliform Survival Ratio) Attained in 'High' Quality and 'Low' Quality Effluents. Effluents Disinfected with Operating Conditions Recommended by the Manufacturer

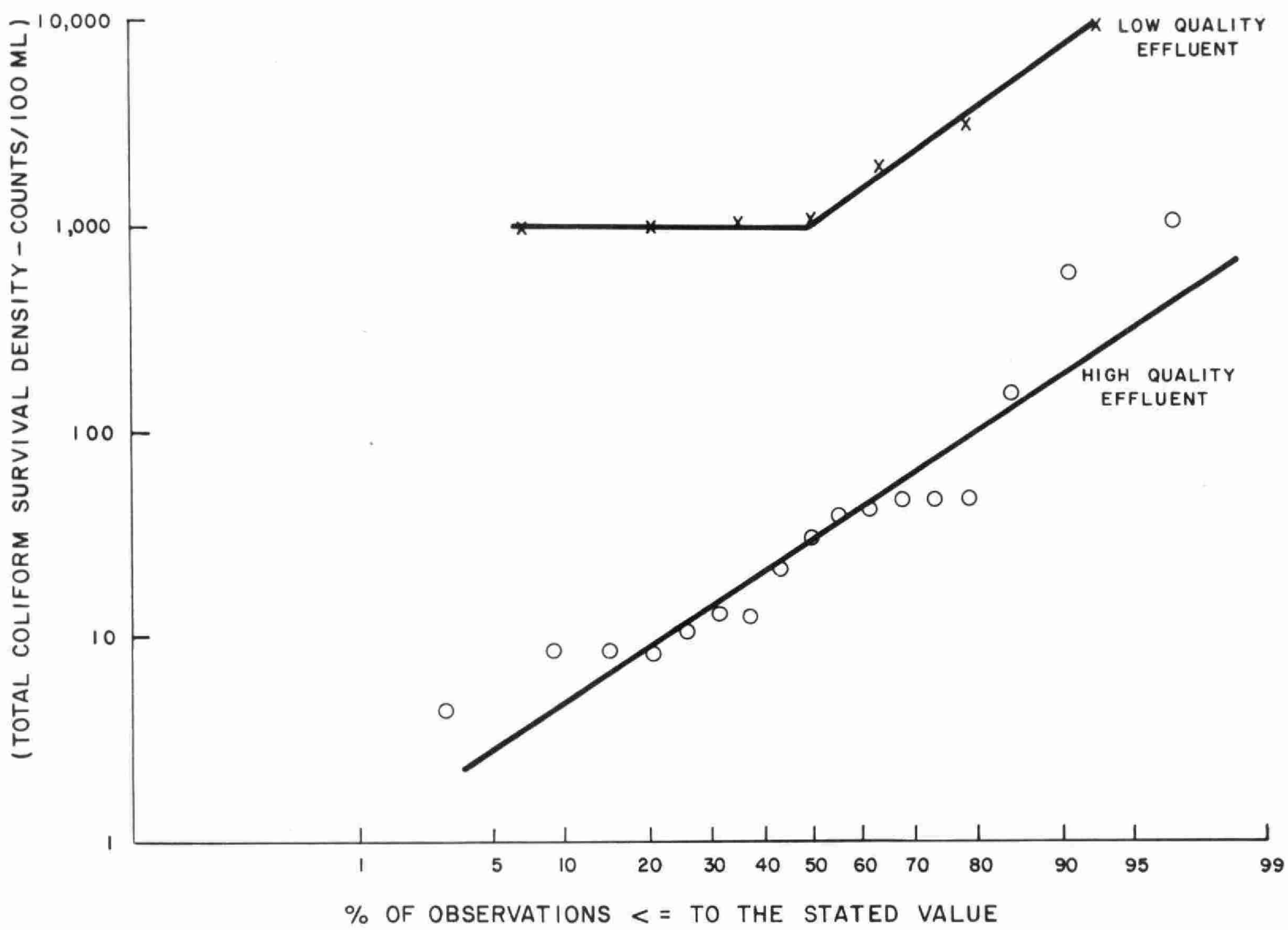

Figure 6 : Percent Frequency Distribution of Log (Total Coliform Survival Density) Attained in 'High' Quality and in 'Low' Quality Effluents. Effluents Disinfected with Operating Conditions Recommended by the Manufacturer

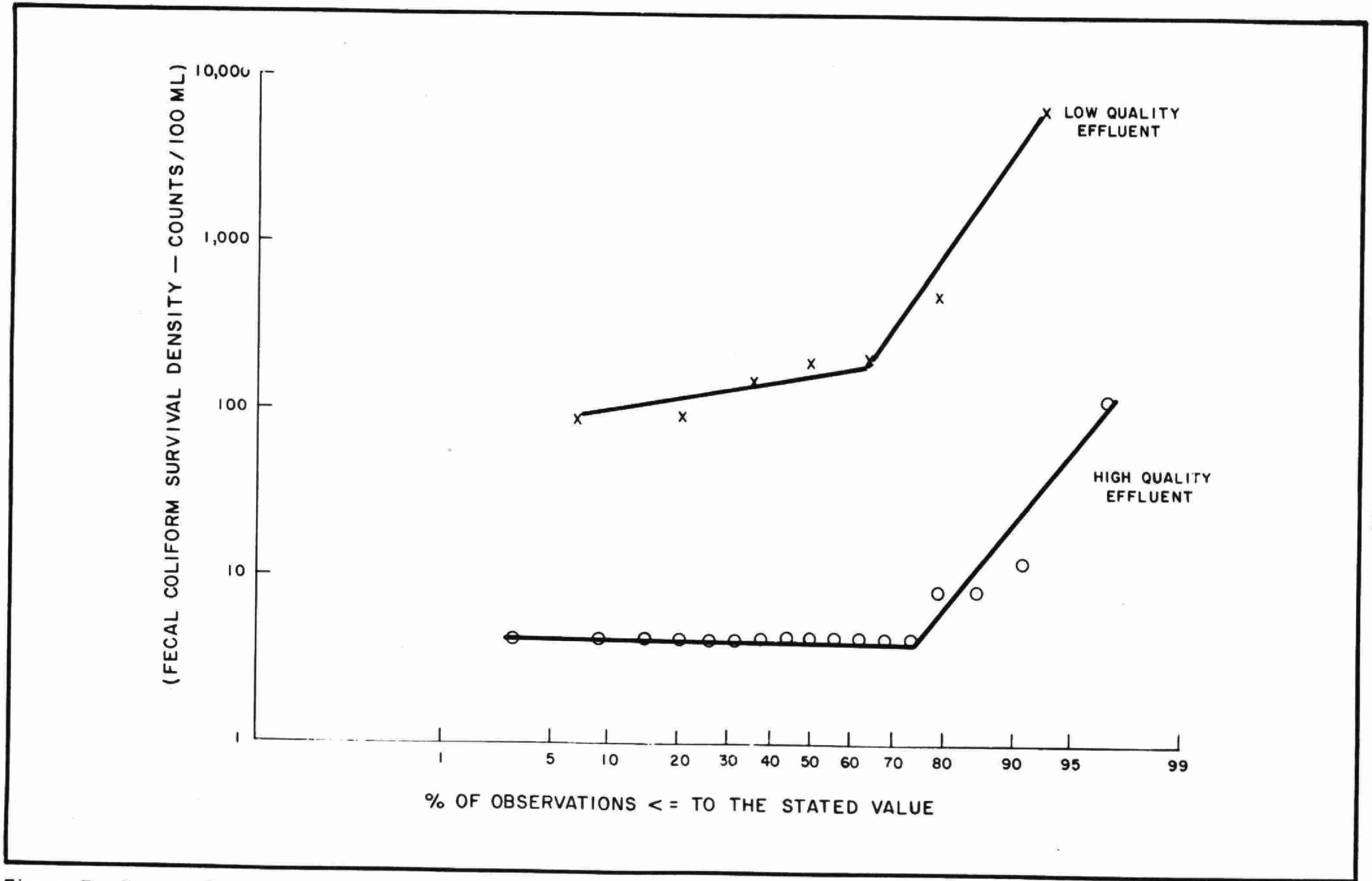

Figure 7 : Percent Frequency Distribution of Log (Fecal Coliform Survival Density) Attained in 'High' Quality and in 'Low' Quality Effluents. Effluents Disinfected with Operating Conditions Recommended by the Manufacturer

TABLE 3 - MEDIAN LOG(TC_r/TC_u), TC_r AND FC_r ATTAINED
WITH 16 UV LAMPS SWITCHED-ON, AND NOMINAL
EXPOSURE TIME BETWEEN 8.3-9.8 SECONDS

EFFLUENT		LOG TC_r/TC_u	TC_r COUNTS/100 ml	FC_r COUNTS/100 ml
"HIGH" QUALITY EFFLUENT	MEDIAN	-3.59	28	4
	15 OF 17 DATA COLLECTED	$\le$-2.92	$\le$144	8
"LOW" QUALITY	MEDIAN	-2.07	1020	188
EFFLUENT	6 OF 7 DATA	$\le$-1.87	$\le$1900	$\le$480

6.3 Analysis Of UV Disinfection Data By The Semi-Mechanistic Model

Forty-four of the entire forty-seven sets of experimental data were pooled together for data analysis. The maximum, minimum, geometric means and coefficients of variation of all the parameters measured are summarized in Table 4. The data was transformed according to the forms suggested by equation (15). Linear correlation coefficients for all pairwise combinations of the transformed data were calculated and presented in Table 5. These coefficients indicate that variation in $\log_{10}(\log_{10}(TC_u/TC_r))$ was significantly related to variations in $\log_{10}(N)$, COD, colour, turbidity and TKN (greater than 99% confidence level). The number of UV lamps switched-on "N" is an indirect measure of reactor volume, hence exposure time. Surprisingly, variation of $\log_{10}(\log_{10}(TC_u/TC_r))$ was not significantly related to the variation in $\log_{10}(F)$ (less than 80% confidence level). The apparent reason for the lack of significance is not immediately known.

A "forward stepwise linear" regression analysis technique (28,29) was applied to search for the most representative operating and quality parameters needed (i.e. least number of parameters needed) to describe the trends displayed by the experimental data. For the effluent disinfected in this study, and for the range of experimental conditions studied, equation (16) was found to sufficiently describe $\log_{10}(TC_r/TC_u)$ attained at the end of UV irradiation.

$$\log_{10}(TC_r/TC_u) = -0.88\ N^{0.69}\ 10^{-0.011\{COD\}} \qquad (16)$$

where $\{COD\}$ = COD concentration in mg/L

TABLE 4 - SUMMARY OF UNDISINFECTED EFFLUENT QUALITY USED FOR UV IRRADIATION STUDY

	TC_u PER 100 ml	FC_u PER 100 ml	COD mg/L	TURB. JTU	TKN mg/L	COLOUR HAZEN UNIT	SS mg/L	BOD_5 mg/L	TOTAL IRON mg/L	TEMP ^oC
MAXIMUM	$1.0x10^6$	$2.7x10^5$	42.0	101	3.0	38	26	23	1.7	21
MINIMUM	$1.6x10^5$	$4.7x10^2$	16.0	0.8	2	5	3	3	0.1	10
G. MEAN	$9.0x10^4$	$5.7x10^3$	26.5	6.4	3.0	21	6	7	0.3	16.5
COEF. OF VAR.	3.25	4.80	1.35	4.48	2.46	2.0	1.7	1.6	2.60	1.25
NO. OF DATA	47	47	47	47	47	47	47	46	47	43

TABLE 5 - LINEAR CORRELATION COEFFICIENT "r" FOR PAIRWISE

COMBINATION OF THE PARAMETERS MEASURED IN THE STUDY

	$\log_{10} \log (TC_u/TC_r)$	$\log_{10}(N)$	$\log_{10} F$	BOD	COD	SS	TURB.	COLOUR	TKN	IRON
$\log_{10} \log_{10} TC_u/TC_r$	1.00	0.73*	0.13	0.11	-0.57*	-0.20	-0.44*	-0.45*	-0.41*	0.23
$\log_{10}(N)$		1.00		-	-	-	-	-	-	
$\log_{10}(t)$			1.00	-	-	-	-	-	-	
BOD				1.00	-0.22	0.52*	-0.03	-0.23	0.13	0.55*
COD					1.00	0.23	0.69*	0.69*	0.60*	-0.30*
SS						1.00	0.57	0.27*	0.45*	0.56*
TURBIDITY							1.00	0.64*	0.28*	-0.04
COLOUR								1.00	0.35*	-0.21
TKN									1.00	-0.02
IRON										1.00

NOTES: N = NUMBER OF UV LAMPS SWITCHED-ON.

t = NOMINAL EXPOSURE TIME (SECONDS).

* INDICATES THAT THE LINEAR CORRELATION COEFFICIENT IS STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL.
CRITICAL r VALUE FOR 44 DATA = (n-1) $_{0.95}$ = (43 x 1.645) = 0.251 WHERE
n = NUMBER OF DATA ANALYSES, AND $_{0.95}$ = NORMAL DISTRIBUTION VALUE AT 95% CONFIDENCE LEVEL.

A copy of the statistical information associated with the regression analysis is given in Appendix II, Table A.II.2. The F-value (82.63) in Table A.II.2 indicates that the relationship between $\log_{10}(\log_{10}(TC_u/TC_r)$, and $\log_{10}(N)$ and {COD} was highly significant (>99.9% confidence). The multiple r-value of 0.89 further implies that approximately 80% of the variation observed in $\log_{10}(\log_{10}(TC_u/TC_r))$ can be related to variations in $\log_{10}(N)$ and {COD}.

The combined effect of the number of UV lamps switched-on, and COD concentration on $\log_{10}(TC_r/TC_u)$ is demonstrated in Figure 8. The lower X-axis in Figure 8 presents the electrical power (watts) required to activate the UV lamps. Effluent flow-rates for the 44 data points plotted ranged from 109 to 318 L/min and are not distinguished in the Figure. The resulting "gross" nominal exposure times ranged from 2.3 to 19.1 seconds. Data with COD concentrations above 30 mg/L are represented by the "X" in Figure 8 and data with COD concentrations below 30 mg/L are represented by the "□". The average COD concentrations for these two groups of data (37 mg/L and 21 mg/L, respectively) were substituted into equation (16) which was then used to draw the two curves through the data points. For $\log_{10}(TC_r/TC_u)$, between -1.0 and -4.0 (equivalent to 90% to 99.99% reduction), the data points scatter very closely around the two fitted curves. Relationship between $\log_{10}(TC_r/TC_u)$ and flowrate "F" was not established in this study.

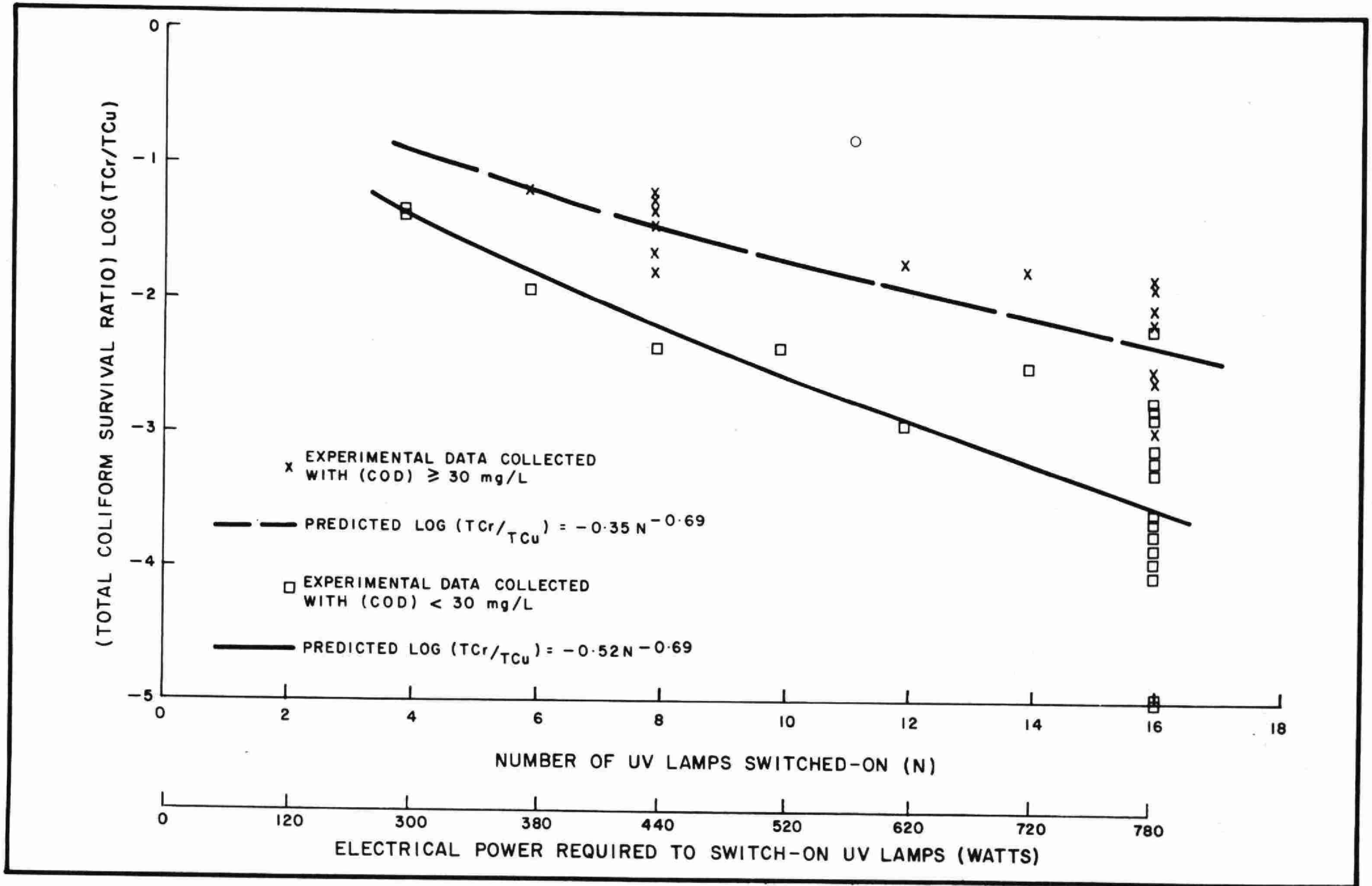

Figure 8: Relationship Between Log (Total Coliform Survival Ratio) and Number of UV Lamps Switched-on (Electrical Power Required) And COD Concentration. Average Nominal Exposure Time = 9.5 Seconds

The linear correlation coefficients presented in Table 5 show that variations in turbidity, colour and TKN were closely related to the variation in COD concentration. Consequently, in this study, COD concentration alone was sufficient to account for the effect of effluent quality on bactericidal efficiency of UV irradiation. However, in a different effluent, other quality parameters such as turbidity, suspended solids, etc, may prove to be a better correlation factor than {COD}. For example, in a recent study (21), UV transmission (or absorbence) was suggested as a possible second process control parameter in addition to flow-pace control of UV dosage.

It should be noted that equation (16) was established with a relatively limited number of data (44 observation), obtained in one WPCP. Equation (16) is therefore, only applicable in the Newmarket WPCP, and with this particular type of UV disinfection unit.

6.4 Maintenance Required For Continuous Operation

Table 6 indicates that the effluent used to evaluate the maintenance required to prevent quartz sheath fouling was of extremely high quality. Nonetheless, after every 24 hour continuous operating period, UV "Point" intensity readings were observed to decrease by an average amount of 33 units (ranged from 2 to 60 units). However, the previous morning UV "Point" intensity reading was easily restored by hand-brushing the quartz sheaths. For operational safety, the UV lamps were switched-off while cleaning, and the whole process took about 5 to 10 minutes to complete. At the end of the entire study (approximately after seven months continuous operation), all 16 quartz sheaths were

TABLE 6

PHYSICAL CHEMICAL QUALITY OF THE UNDISINFECTED EFFLUENT USED

FOR THE EVALUATION OF MAINTENANCE REQUIREMENT

	TURBIDITY JTU	COLOUR Hz UNIT	SS mg/L	TKN mg/L	BOD_5 mg/L	COD mg/L	TOTAL mg/L
ARITH. MEAN	4.1	21	6	2.2	8	24	0.53
ARITH. STD. DEV.	1.6	14	1	2.1	4	4	0.19
NO. OF SAMPLES ANALYZED	4	4	4	4	4	4	4

observed to have a thin coat of yellowish film which was believed to be ferric precipitate (not analysed). The yellowish film was easily washed off with dilute hydrochloric acid.

Quartz sheath fouling observed in this study is not being considered as a serious setback for UV disinfection process, since most large scale UV disinfection units are designed with an automatic wiping system.

7.0 UV DISINFECTION COST

Based on the results and experience obtained in this study, UV disinfection costs for three different WPCP design capacities (327, 545 and 1090 m^3/day) were estimated. Disinfection unit purchase costs, UV lamp and quartz sheath replacement costs and electrical power required for operating the three units as quoted by the Canadian representative Water Refining Company, in 1979, are presented in Table 7. Annual costs (operating plus capital) are presented in Table 8. The costs were derived with the following assumptions:

- 35% of the disinfection unit purchase price is allowed for engineering and installation costs;
- all capital costs carry an interest rate of 12%, compounded semi-annually. Amortization period is 20 years;
- UV disinfection unit is equipped with automatic wiping system. Quartz sheaths are to be acid-washed approximately once every three months. Approximately 26, 52 and 104 man-days per year are required to operate the three disinfection units, respectively;
- unit labour cost including cost for supervision is $20,000 per man per year. Two hundred and forty-five working days per man-year is assumed;
- electrical power cost is 3.0¢/Kw-hr;
- UV lamps in continuous service have one-year's life. Lamp replacement cost is $97.76 per lamp;

TABLE 7

INFORMATION ON ULTRA-VIOLET DISINFECTION UNITS MANUFACTURED

BY AQUAFINE LIMITED, CALIFORNIA, USA

MODEL	DESIGN CAPACITY m^3/DAY	IMP. GALLON/ DAY	UNIT* PRICE ($)	NO. OF UV LAMPS PER UNIT	ELECTRICAL POWER REQUIRED FOR UV LAMPS (Kw/hr)
WT 600	327	72,000	8,414	16	0.8
WT 100	545	120,000	10,718	26	1.3
WT 200	1090	240,000	14,291	52	2.6

* Price exclusive of sales tax. F.O.B. Toronto, Ontario.

TABLE 8

ANNUAL UV DISINFECTION OPERATING COSTS

(TO THE NEAREST DOLLAR)

	WPCP DESIGN CAPACITY (m^3/DAY)		
	327	545	1090
ANNUAL AMORTIZED CAPITAL COST	1510	1923	2565
LABOUR COST	2123	4245	8490
POWER COST FOR UV ENERGIZING LAMPS	210	342	683
UV LAMP REPLACEMENT COST	1564	2542	5084
MISCELLANEOUS PARTS REPLACEMENT AND MAINTENANCE COSTS	163	236	400
TOTAL ANNUAL DISINFECTION-COST ($)	5570	9288	17222
DISINFECTION COST (¢/m^3)	4.67	4.67	4.33
CHLORINATION DISINFECTION COST FOR A 454 m^3/D - WPCP (¢/m^3)		2.26	
CHLORINE + DECHLORINATION DISINFECTION - COST FOR A 454 m^3/DAY WPCP. (¢/m^3)		3.67	
OZONE DISINFECTION COST FOR A 454 m^3/D - WPCP (¢/m^3)		9.60	
CHLORINE DIOXIDE DISINFECTION COST FOR A 454 m^3/D - WPCP (¢/m^3)		8.54	

- the quartz sheath shielding the UV lamp is to be replaced once per ten years at a cost of \$98.75 per sheath. An additional 1% of the disinfection unit purchase cost is allowed for miscellaneous parts/ replacement and maintenance costs.

Table 8 indicates that UV disinfection costs in small WPCP's would be between 4.33¢ and 4.67¢ per m^3 effluent disinfected. For purposes of comparison, chlorine, ozone and chlorine dioxide disinfection costs, and chlorination plus dechlorination costs for nitrified effluent in a 454 m^3/day WPCP (7) are also included in Table 8.

Table 8 demonstrates that UV disinfection cost is approximately 1.2 to 1.3 times of chlorination plus dechlorination cost, and is approximately 49% and 55% of the costs estimated for using ozone and chlorine dioxide, respectively. It can, therefore, be concluded that UV disinfection process is the most cost competitive alternative to chlorination-dechlorination process in a highly nitrified tertiary WPCP.

Another important point to be noted in Table 8 is that the annual UV lamp replacement cost is about 27.5%-29.5% of the total UV disinfection cost. It has been reported that large discount rates are available when UV lamps are bought in bulk quantities. The lowest cost per UV lamp was quoted at \$30 per lamp (31) which implies that in large WPCP's, UV disinfection is more competitive than presently estimated.

8.0 NOMENCLATURE

C_i	Concentration of Contaminant i
D	UV Dosage
E	Extinction Coefficient
F	Effluent Flowrate
I	UV Intensity (micro-watts/cm^2)
I_o	UV Intensity Emitted by One UV Lamp
I_p	UV Intensity Meastured at a Point
J_i	E_iL
K_o	Overall UV Disinfection Rate Constant
K_o'	Modified Overall UV Disinfection Rate Constants
K_1	Exponent for N
K_2	Exponent for F
L	Mean Distance Between UV Lamps and Contaminants
M	Number of Bacterial Organisms in Sewage Effluent
M_u	Number of Bacterial Organisms before UV Irradiation
M_r	Number of Bacterial Organisms after UV Irradiation
MLVSS	Mixed Liquor Volatile Suspended Solids
N	Number of UV Lamps Switched On
TC	Total Coliform Counts/100 ml
TC_u	Total Coliform Counts/100 ml in Undisinfected Sewage Effluent
TC_r	Total Coliform Counts/100 ml in Disinfected Sewage Effluent
n	Number of Sewage Effluent Contaminants That Would Affect the Bactericidal Efficiency of UV Disinfection
t_a	True Exposure Time to UV Irradiation
t	Nominal Exposure Time to UV Irradiation
t_e	Gross Nominal Exposure Time (min)
V_e	Effective Volume per UV Lamp for Disinfection
V_{te}	Total Effective Volume for UV Disinfection

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APPENDIX I

RESIDENCE TIME CHARACTERISTICS OF THE AQUAFINE WT-60 UV DISINFECTION UNIT

A.I.1 Introduction

The residence time characteristics of the Aquafine WT-60 UV disinfection unit was determined by dye-tracer tests.

Procedures

The equipment and procedures as detailed by D. G. Deaner (1) was used to obtain the dye-tracer curves. Influent flowrates through the disinfection unit were varied from 30% to 100% of design capacity (227 L/min) in seven steps. Dye-tests at each flowrate were run in triplicate and results were averaged for each run.

A.I.3 Results And Discussion

Only one dye-tracer curve is presented in Figure A.I.1 for the purpose of illustration. All dye-tracer curves were observed to have similar shapes as Figures A.I.1. The calculated residence time distribution parameters are plotted against effluent flowrate in Figure A.I.2.

Figure A.I.2 demonstrates that residence time characteristics of the Aquafine WT-60 disinfection unit remain fairly constant for effluent flowrates up to 180 L/min, which is about 80% of its design capacity. The Morrill Index (t_{10}/t_{90}) varies between 2.7 and 2.9, indicating moderate back mixing[(2)]. Above 180 L/min, this index rises sharply, reaching 4.5 at design flow.

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Similarly, the index of short-circuiting (t_i/T_n) remains between 0.5-0.6 for effluent flowrate up to 180 L/min. It then drops sharply, reaching 0.12 at design flow.

The long tapering tails on the dye-tracer curves (Figure A.I.1) indicate that there are some dead spaces within the disinfection unit. These dead spaces probably are flow "shadows" behind the shallow baffles in the disinfection chamber. Total washout time is on the order of 4 to 5 nominal detention times.

A.I.4 Conclusions

The Aquafine WT-60 disinfection unit approximates a plug flow reactor with moderate backmixing up to a flowrate of 180 L/min. Above this flow rate the disinfection unit becomes essentially a backmix reactor. At design flow the minimum contact time "t_d" is approximately 1 second.

A.I.5 Definition Of Terms

t_i - elapsed time between dye injection and first tracer indication at sampling point;

t_p - elapsed time between dye injection and peak dye tracer concentration; also known as modal time;

t_g - elapsed time between dye injection and the centre of gravity of the eluted dye tracer curve; also known as mean detention time;

t_d - elapsed time for first appearance of dye;

t_n/t_n - any of the above times divided by the nominal detention time yielding a dimensionless index;

Morrill Index - index of backmixing calculated as t_{90}/t_{10}, i.e. time for 90% of the dye-tracer to pass through the system divided by the time for 10% of the tracer to pass.

FIGURE A.1.1

TYPICAL DYE TRACER TEST CURVE

(DYE TEST # 6.2)

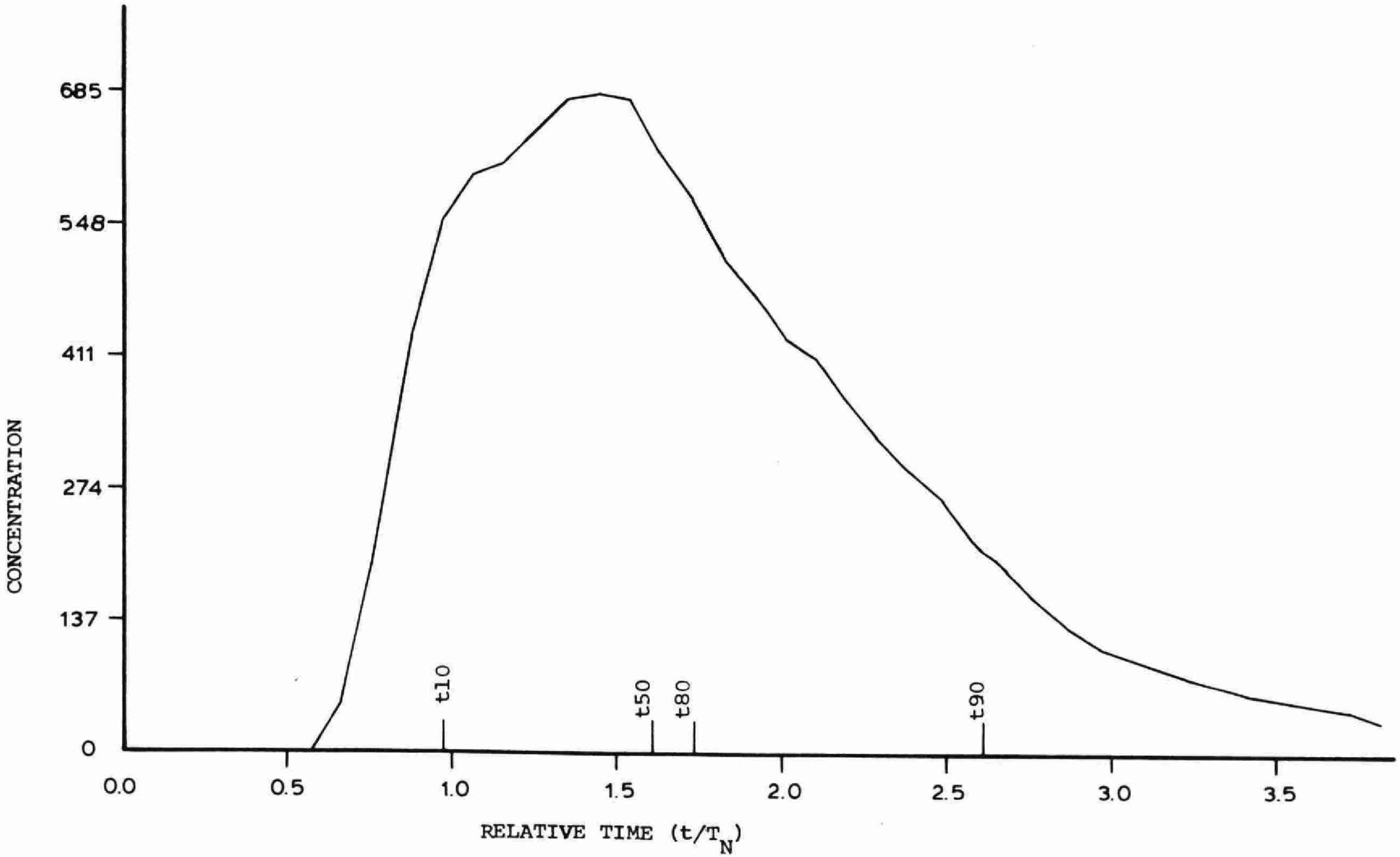
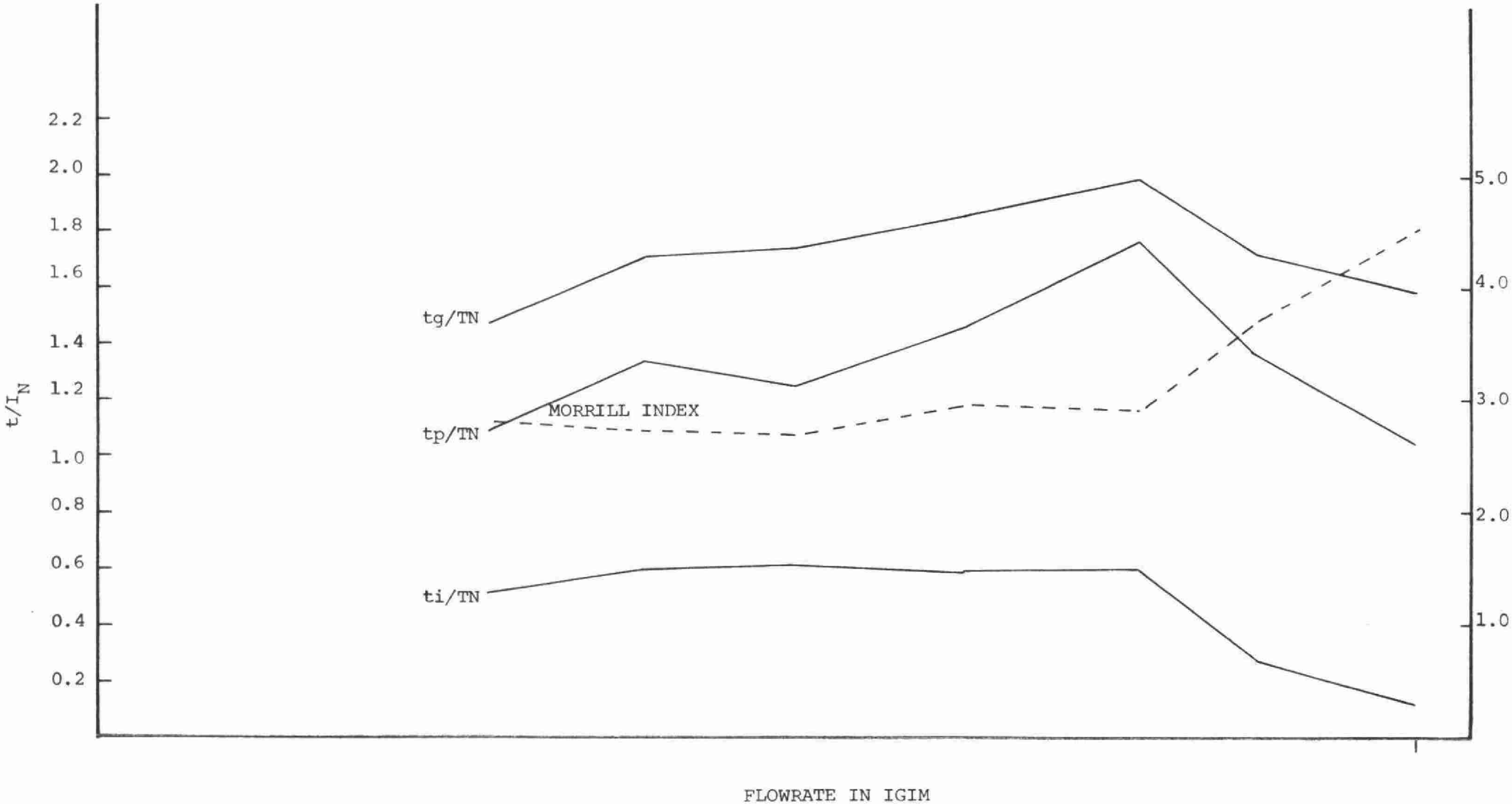


FIGURE A.1.2 - RESIDENCE TIME CHARACTERISTICS FOR
AQUAFINE WT 60 UV DISINFECTION UNIT

ti/TN - INDEX OF SHORT CIRCUITING (TIME FOR FIRST DYE TRACER TO APPEAR AT EFFLUENT)
tp/TN - INDEX OF MODAL DETENTION TIME (TIME TO PEAK TRACER CONCENTRATION)
tg/TN - INDEX OF MEAN DETENTION TIME (CENTRE OF GRAVITY)



APPENDIX II

RAW EXPERIMENTAL DATA

AND

STATISTICAL INFORMATION ASSOCIATED WITH EQUATION 17

TABLE A.II.1-RAW DATA FOR UV DISINFECTION STUDY CONDUCTED IN NEWMARKET TERTIARY WPCP

N	Q	TC_u	TC_r	$Log(\frac{TC_r}{TC_u})$	FC_u	FC_u	$Log(\frac{FC_r}{FC_u})$	BOD_5	COD	SS	TURB.	COLOR	TKN	NO_2	NO_3	Fe	TEMP.
16	318	17000	4	-3.628	4700	4	-3.070	12	26	4	5.0	20	4.8	0.4	11.0	0.2	11
16	318	19000	20	-2.978	740	4	-2.267	7	22	5	4.0	10	1.7	---	13.0	0.4	11
16	318	28000	4	-3.845	2800	4	-2.845	12	20	5	2.3	20	7.2	---	11.0	0.2	10
16	226	830000	8	-5.016	38000	4	-3.978	17	26	10	5.5	15	5.0	---	10.0	0.7	10
16	226	140000	12	-4.061	4200	4	-3.021	7	20	10	5.5	5	2.0	---	9.0	0.8	11
16	226	170000	44	-3.578	19000	8	-3.376	--	23	7	5.5	15	5.3	---	10.0	0.7	12
16	250	290000	140	-3.304	24000	12	-3.301	23	--	26	7.5	15	6.0	---	9.0	1.7	12
16	250	480000	3000	-2.204	89000	6000	-1.171	21	31	12	6.5	15	5.6	---	10.0	1.7	12
16	250	320000	560	-2.760	31000	110	-2.442	10	20	7	4.0	5	6.0	12.0	0.2	0.4	11
16	213	140000	1900	-1.872	11000	150	-1.871	6	35	7	4.8	26	8.2	0.5	0.9	0.1	18
14	213	130000	2100	-1.784	10000	140	-1.842	6	36	8	4.3	28	8.6	0.5	0.9	0.3	16
12	213	160000	3000	-1.730	1000	140	-0.854	6	36	8	4.4	30	9.0	0.5	0.9	0.2	16
10	213	30000	20000	-0.176	20000	260	-1.886	8	38	10	4.4	29	10.0	0.5	0.9	0.4	17
8	213	180000	10000	-1.255	17000	240	-1.850	8	38	9	5.0	30	11.0	0.6	1.0	0.2	17
6	213	2000000	130000	-1.187	18000	900	-1.301	7	37	8	3.8	25	12.0	0.6	0.9	0.1	18
16	109	100000	250	-2.263	11000	44	-2.398	5	35	6	37.0	30	4.8	0.6	13.0	0.0	20
8	109	110000	1700	-1.793	1500	110	-1.127	4	35	7	35.0	30	6.2	0.6	12.0	0.0	19
16	163	300000	300	-2.994	14000	560	-2.398	4	35	6	25.0	30	7.2	0.6	12.0	0.0	19
16	213	350000	1000	-2.535	26000	88	-2.470	4	34	6	33.0	27	8.4	0.6	11.0	0.1	19
16	277	74000	920	-1.905	3000	160	-1.262	6	35	9	66.0	26	3.4	0.5	15.0	0.2	17
8	277	47000	2900	-1.207	9000	640	-1.148	6	36	9	65.0	30	3.4	0.5	15.0	0.2	18
8	226	56000	2000	-1.443	4000	310	-1.108	6	36	9	58.0	27	3.4	0.5	15.0	0.4	18
16	226	79000	940	-1.924	6000	84	-1.854	7	36	10	56.0	29	4.0	0.6	15.0	0.2	16
16	226	110000	940	-2.068	11000	480	-1.360	9	42	16	101.0	35	5.6	0.7	15.0	0.9	16
8	226	110000	2500	-1.648	8000	600	-1.125	9	42	16	100.0	35	6.0	0.7	15.0	0.4	16
8	226	110000	5000	-1.326	150000	2000	-1.875	9	42	15	92.0	38	7.2	0.7	14.0	1.0	17
16	226	140000	980	-2.155	270000	200	-3.319	9	40	14	89.0	36	7.4	0.7	14.0	0.9	16
16	226	21000	12	-3.243	630	4	-2.197	8	21	4	2.0	26	2.4	0.5	16.0	0.5	21
16	226	180000	20	-3.954	31000	4	-3.889	7	23	6	5.5	38	1.2	0.4	18.0	0.4	21
16	226	760000	1000	-2.881	100000	4	-4.398	14	27	5	5.5	5	5.4	0.9	13.0	0.8	21

TABLE A.II.1 - CONTINUED

N	Q	TC_u	TC_r	$\log(\frac{TC_r}{TC_u})$	FC_u	FC_r	$\log(\frac{FC_r}{FC_u})$	BOD_5	COD	SS	TURB.	COLOR	TKN	NO_2	NO_3	Fe	TEMP.
16	226	940000	10	-4.973	1000	4	-2.398	4	26	6	2.5	25	1.2	0.1	13.0	0.4	21
16	226	19000	9100	-0.320	470	192	-0.398	10	21	4	60.0	23	1.8	0.9	14.0	0.4	21
16	226	210000	44	-3.679	7700	4	-3.284	10	24	8	3.5	21	1.4	0.7	18.0	0.6	19
16	226	37000	28	-3.121	2700	4	-2.829	6	18	7	3.0	16	1.0	0.3	17.0	0.5	18
16	226	73000	44	-3.220	6100	8	-2.882	7	21	6	4.0	18	2.4	0.8	16.0	0.7	19
16	226	71000	8	-3.948	5000	4	-3.097	3	21	3	1.4	15	1.0	0.0	14.0	0.3	19
16	226	67000	36	-3.270	3000	4	-2.875	3	21	3	1.4	20	1.0	0.0	14.0	0.3	19
16	226	33000	40	-2.916	1000	4	-2.407	3	21	3	1.4	20	1.0	0.0	14.0	0.3	19
14	226	24000	76	-2.499	1100	4	-2.447	3	21	3	1.4	20	1.0	0.0	14.0	0.3	19
12	226	32000	36	-2.949	1100	8	-2.154	5	22	3	1.4	20	1.2	0.5	16.0	0.3	19
10	226	26000	120	-2.351	1300	8	-2.224	5	22	3	1.4	20	1.2	0.5	16.0	0.3	19
8	226	37000	180	-2.353	1400	12	-2.076	5	22	3	1.4	20	1.2	0.5	16.0	0.3	19
6	226	32000	380	-1.930	1500	24	-1.802	5	22	3	1.4	20	1.2	0.5	16.0	0.3	19
16	226	44000	80	-3.740	700	4	-2.243	9	17	4	1.2	21	0.8	0.2	20.0	0.3	--
4	226	40000	1700	-1.362	1100	44	-1.378	9	16	3	0.8	20	0.8	0.1	19.0	0.3	--
16	226	16000	4	-3.682	1300	4	-2.502	8	16	3	0.9	16	0.6	0.0	20.0	0.2	--
4	226	26000	1000	-1.415	2200	60	-1.564	10	17	4	1.2	17	0.8	0.1	23.0	0.8	--

Notes:

N = NUMBER OF UV LAMPS SWITCHED-ON   Q = EFFLUENT FLOWRATE (L/MIN)

TC_u = TOTAL COLIFORM DENSITY IN UNDISINFECTED EFFLUENT (COUNTS/100 mL)

TC_r = TOTAL COLIFORM DENSITY IN UV DISINFECTED EFFLUENT (COUNTS/100 mL)

FC_u = FECAL COLIFORM DENSITY IN UNDISINFECTED EFFLUENT (COUNTS/100 mL)

FC_r = FECAL COLIFORM DENSITY IN UV DISINFECTED EFFLUENT (COUNTS/100 mL)

TURB. = TURBIDITY (JTU)   COLOR = COLOR (HAZEN UNIT)

Fe = TOTAL IRON CONCENTRATION (mg/L)   TEMP. = TEMPERATURE (^{o}C)

BOD_5 = BIOLOGICAL OXYGEN DEMAND (mg/L)   COD = CHEMICAL OXYGEN DEMAND (mg/L)

SS = SUSPENDED SOLIDS CONCENTRATION (mg/L)

TABLE A.II.1 - CONTINUED

TKN = TOTAL KJELDAHL NITROGEN CONCENTRATION (mg/L as N)

NO_2 = NITRITE CONCENTRATION (mg/L as N)

NO_3 = NITRATE CONCENTRATION (mg/L as N)

TABLE A.II.2 - STATISTICAL OUTPUT OF THE REGRESSIONAL ANALYSIS USED TO ESTABLISH EQUATION 12

MEAN VARIANCE AND STD. DEV.

VARIABLE	MEAN	VARIANCE	STD. DEV.
1	3.92423E-01	2.96839E-02	1.72290E-01
2	1.09655E 00	3.00610E-02	1.73381E-01
3	2.76364E 01	6.72600E 01	8.20122E 00

SIMPLE CORRELATION MATRIX-R

1.000	0.730	-0.573
	1.000	-0.078
		1.000

ESTIMATION OF PARAMETERS

VAR.	COEFF.	ST. ERROR	T-VALUE
2	6.8504E-01	6.9405E-02	9.8702E 00
3	-1.0913E-02	1.4673E-03	7.4375E 00

INTERCEPT = -0.05716

ANOVA TABLE

SOURCE	SS	DF	MS
REGRESSION	1.02268	2.00000	0.51134
RESIDUAL	0.25373	41.00000	0.00619

F-VALUE = 82.63
S.E. OF EST. = 0.08
MULT. R. = 0.90
ADJ. MULT. R. = 0.89

COVARIANCE MATRIX

8.0609E-03	-5.5027E-03	-6.8251E-05
-5.5027E-03	4.8171E-03	7.9806E-06
-6.8251E-05	7.9806E-06	2.1529E-06

$$\text{Log } ({}^{TC}r/TC_u) = -0.88\ N^{0.69}\ 10^{-0.01\ [COD]}$$

variable 1 = log log $({}^{TC}u/TC_r)$

variable 2 = log N (N = number of UV lamps switched-on).

variable 3 = {COD} ({COD} = effluent COD concentration mg/L).